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13. ABSTRACT (Maximum 200 words) <p>1. Theoretical modeling of some of the problems associated with the above described topics presented a challenge. The complex nature of the geometry as well as the materials involved precluded the application of purely analytical methods for their solution. We were able to use conventional BEM for topic #2 and a hybrid form of the FEM for topic//4, but these methods did not work well for the other topics. A new numerical technique, called the volume integral equation method (VIEM), was developed to calculate the elastostatic as well as elastodynamic fields in structural components of large lateral extent containing localized multiple inclusions and flaws. The technique has clear advantages in accuracy and efficiency over conventional FEM and BEM in calculating the effects of local "microstructure" under remote loading. This is considered to be a major contribution to the literature in structural and solid mechanics.</p> <p>2. A detailed study of the mechanisms for the degradation of SiC/Ti composites under fatigue loading was carried out leading to the following accomplishments.</p>			
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October 9, 2000

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**Re: Final Technical Report for DURIP95 Grant #F49620-95-1-0491**

Dear Tom:

The Final Technical Report for the equipment grant is enclosed. Sorry about the delay. I was under the (mistaken) impression that the report for #0320, that was submitted in May '99, would be adequate, since the equipment purchased through the grant was in support of research carried out under #0320.

Sincerely,

Ajit

cc: Craig Geber, Cindy Gilbert

12 OCT 2000

**DURIP95/RESEARCH EQUIPMENT  
FOR  
DAMAGE CHARACTERIZATION IN STRUCTURAL SOLIDS**

AFOSR Grant F49620-95-1-0491

**Final Technical Report  
October 9, 2000**

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### **Research Issues Addressed**

The equipment purchased under this grant was utilized for research directed toward developing the knowledge base required for characterization of materials degradation caused by corrosion, fatigue and dynamic loads in metallic and composite structural components. The tasks carried out in the project can be broadly classified into two areas of research, namely,

#### **A. Integrity of Structural Components.**

#### **BI. Nondestructive Evaluation (NDE).**

Within these broad areas the following specific topics were investigated:

1. Calculation of elastostatic and elastodynamic fields in solids containing multiple inclusions and cracks.
2. Micromechanics of damage in SiC/Ti composites under static and fatigue Loading.
3. Mechanics of failure of aluminum panels with multiple holes and corrosion pits.
4. Ultrasonic NDE of corrosion damage around rivet holes and inside lap joints in aluminum panels.
5. Ultrasonic characterization of the degradation of GR/EP and SiC/Ti composites under static, fatigue and dynamic loads.
6. Development of a wave-based acoustic emission (AE) technique to detect the presence of small hidden flaws in metals and composites.
7. Investigation of a "laser shock peening" (LSP) process for improving fatigue life and fatigue strength of aluminum alloys.

## Research Highlights

1. Theoretical modeling of some of the problems associated with the above described topics presented a challenge. The complex nature of the geometry as well as the materials involved precluded the application of purely analytical methods for their solution. We were able to use conventional BEM for topic #2 and a hybrid form of the FEM for topic #4, but these methods did not work well for the other topics. A new numerical technique, called the volume integral equation method (VIEM), was developed to calculate the elastostatic as well as elastodynamic fields in structural components of large lateral extent containing localized multiple inclusions and flaws. The technique has clear advantages in accuracy and efficiency over conventional FEM and BEM in calculating the effects of local "microstructure" under remote loading. This is considered to be a major contribution to the literature in structural and solid mechanics.

2. A detailed study of the mechanisms for the degradation of SiC/Ti composites under fatigue loading was carried out leading to the following accomplishments.

- (a) The VIEM was used to analyze the damage mechanism of SiC/Ti composites when the SiC fibers are subject to transverse load. To our knowledge, this is the first time that a rigorous mechanics-based explanation of the failure of these materials at unexpectedly low loads and at fatigue cycles has been given. These studies are extremely important in the development of new intermediate temperature metal matrix composites.
- (b) Experimental and analytical studies were carried out to better understand the effect of microstructural parameters and multiple processing cycles on the fatigue behavior and damage evolution in SCS-6/Ti-22Al-23 Nb Orthorhombic Titanium Aluminide Composites. A new analytical model to simulate the evolution of matrix cracking, degradation of mechanical properties and distribution of fatigue life of these composites under various applied cyclic stresses was developed. The propagation of matrix cracks was modeled by a fiber bridging model that incorporates the effect of fiber breakage on crack growth. The simulated crack propagation rate, residual stiffness, residual tensile strength and fatigue life were found to correlate well with the experimental results.
- (c) The fatigue damage evolution and property degradation of SiC fiber-reinforced Ti-15V-3Al (disordered Ti), Ti-25Al-10Nb (order  $Ti_3Al$ ) and Ti-22Al-23Nb (orthorhombic  $Ti_2AlNb$ ) composites was investigated. The mechanisms of fatigue damage initiation, propagation and failure have been well-characterized.
- (d) A mechanism-based micromechanical model and Monte Carlo simulation to predict fatigue life of fiber-reinforced titanium matrix composites has been developed. The predicted matrix crack growth rates, residual stiffness, residual tensile strength and fatigue life correlated well with the experimental results.
- (e) The effect of fiber coating to improve the interfacial compatibility and to suppress the fatigue crack initiation at the fiber/matrix interface has been carefully studied. We have successfully demonstrated that fiber coating is an effective approach to improve the fatigue resistance of titanium matrix composites.
- (f) The fatigue behavior and damage progression of a SiC fiber-reinforced ductile titanium and brittle titanium aluminide hybrid laminated composite has been examined. The hybrid laminated composite is expected to be used at higher temperatures compared with convention

disordered titanium matrix composites and also to have improved damage tolerance in comparison with the ordered titanium aluminide composites.

- (g) An interface-controlled fatigue cracking model to predict the fatigue crack initiation from the micronotches at the ruptured fiber/matrix interface has been developed. The model can accurately predict the critical interfacial reaction thickness and maximal applied stress necessary to suppress the fatigue crack initiation at the rupture interface. This information is critical for designing fatigue-resistant components.

3. The stress concentration in typical structural aluminum panels containing multiple holes and corrosion pits with a large variety of shapes, sizes and locations, were calculated by means of BIEM as well as FEM. The numerical simulations resulted in two major discoveries: (1) the effectiveness of stop-holes at the tips of existing cracks can be improved through the introduction of additional holes near the tips without any detrimental effect on the strength of the panel; (2) the degree of corrosion damage can be characterized in terms of the probability of failure (due to initiation and propagation of plastic deformation) in a panel containing a random distribution of corrosion pits. We have carried out a few simulations and preliminary experiments to test the validity of these results. Both results are of great significance in improving the safety and integrity of aging structures. However, more extensive numerical simulations and laboratory tests on real specimens are needed before the technique can be used in field environments.

4. The feasibility of using remotely launched plate guided waves to characterize corrosion damage in rivet holes and lap joints in typical aging aircraft was carefully examined. A hybrid method called the global-local finite element method (GLFEM) and laboratory experiments have been used to study problem. It has been found that it is indeed possible to detect the presence of corrosion or cracking of the rivet holes.

5. A relatively new immersion ultrasonic method using dual transducers in a pitch catch arrangement was developed to determine small changes in the stiffness constants of composites caused by exposure to hostile environments. We have been successful in determining the stiffness reduction of graphite/epoxy panels subject to fatigue or thermal exposure and of SiC/Ti subject to fatigue. To our knowledge, this is a unique capability, that no other group in this country has been able to achieve. This technique has the potential for field applications to monitor the degradation of composite structures.

6. In the past, analysis of acoustics emission signal (AE) has been used, with limited success, for in-service monitoring of the fracture and failure of a variety of structures. Conventional AE is based on event-counts and empirical analysis of the counts and other related data that can often be highly subjective, and may give false indications regarding the status of the structure. A new wave-based AE technique in which the individual AE waveforms are analyzed to extract source information was developed. The distinguishing features of the waves from various types of microfracture in both aluminum and composite specimens were identified and the theoretical simulations agreed remarkably well with results from carefully designed laboratory tests. A pattern recognition technique was applied to the signals to identify various types of fracture in laboratory specimens. This work is of great importance in developing practical nondestructive tools for structural health monitoring. The technique was applied to the following specific problems.

(a) Fatigue induced acoustic emission from aluminum alloys.

In the fatigue study, single-edge notched specimens were used and AE signals were collected at various crack growth rates, ranging from 0.1 to 50  $\mu\text{m}$  per cycle. Characteristics of AE signals generated were analyzed by pattern recognition via a trained K-nearest neighbor classifier. The classified waveforms can be correlated with different types of AE sources (crack advances, crack opening/closing, and fretting) in terms of crack growth rates, stress levels and plate-wave propagation modes. The use of pattern recognition analysis holds much promise in applying AE methods in airframe inspection. Wu's MS thesis study examined fatigue-induced AE signals in 2024-T4 alloy. Three basic waveforms were established and the pattern recognition analysis was applied to the data set in combination with the stress level data. In Birge's MS work, he used 7075 alloy in T6 and annealed condition as well as the high-purity version, 7475 alloy, in the cold-worked condition. Similar waveform patterns are found, but a few variations for each were recognized as well. Cold work reduced AE activities, while annealing increased them, mainly from crack face interference. In the low crack growth rate regime, AE activity is low and this presents a challenge in real-life NDE applications.

(b) Waveform analysis in advanced structural composites. AE waveform analysis in advanced structural composites is quite complex due to the presence of various microfracture modes. The relationship between the surface response and microfracture modes in composite laminates is studied to establish the theoretical background for waveform analysis of AE signals. Lamb waves produced by arbitrary internal sources in unidirectional and cross-ply composite laminates are predicted. Laboratory experiments are performed to validate the theoretical models. The results of this work along with the pattern recognition analysis techniques should be useful in developing practical non-destructive testing tools to monitor damage initiation and evolution in composite structures under monotonic and cyclic loading conditions. For example, AE waveforms due to fiber fracture, matrix cracks and delamination can be clearly differentiated. Because of high attenuation of acoustic waves in fiber-reinforced composites, global damage monitoring requires perhaps an excessive number of sensors. However, wave-based AE methods can be effective in the evaluation of localized damages.

7. Laser shock peening produces a compressive residual stress on the surface of the specimen that can significantly improve the fatigue life and fatigue strength of metallic alloys. The residual stresses appear to extend to depths of 1mm or higher; this is much higher than what can be achieved with conventional shot peening. However, all the experimental work conducted so far in Europe are based upon very thick specimen ( $> 1\text{ cm}$ ). The optimum laser shock conditions for thin-section specimen to obtain the best residual stress profile has not been established. Exploratory research on using laser shock peening to improve the fatigue life of thin-section 2024 Al alloys was conducted. X-ray diffraction was used to measure the residual stress distribution through the thickness of specimen. The effect of laser shock peening on the fatigue behavior of aluminum alloys for aircraft structures was also investigated. It was successfully demonstrated that laser shock peening is a very effective approach for suppressing the fatigue crack initiation and crack growth in aluminum alloys.

**PERSONNEL SUPPORTED**

None



## PUBLICATIONS

### A. Refereed Journals

Wang, P.C., Jeng, S.M., Yang, J.-M., and Mal, A.K., "Fatigue Life Prediction of Fiber-Reinforced Titanium Matrix Composites", *Acta Mater.*, Vol. 44, pp. 1097-1108, 1996.

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Mal, A.K., Yang, R.-B., and Yang, J.-M., "Characterization of Fiber-Matrix Interface Degradation in a Metal Matrix Composite", *Rev. of Progr. in QNDE*, Vol. 14, pp. 1465-1472, 1995.

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### **C. Presentations**

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"Wave Propagation in Anisotropic Composite Plates," *Progress in Acoustic Emission*, VIII, The Japanese Society for NDI, pp. 1-10, 1996.

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"Interaction of Lamb Waves with Defects in a Semi-infinite Plate," *Rev. Progr. in QNDE*, Vol. 16, pp. 397-404, 1996.

"Analysis of Multiple Inclusion-Crack Problems Using a Volume Integral Equation Method", Symposium on Mechanics and Design, University of Toronto, May 6-9, 1996 (invited).

"Micromechanical Damage Evolution in Composites", ASME Mechanics and Materials Conference, The Johns Hopkins University, June 12-14, 1996 (invited).

"Elastic Wavefield Calculations in Strongly Heterogeneous Media", Second National Congress in Computational Mechanics, Technical University of Crete, Greece, June 26-28, 1996 (invited).

"Plate Wave Characterization of Stiffness Degradation of Composite Laminates Under Fatigue Loading", *Rev. Prog. in QNDE*, Brunswick, Maine, July 29, 1996 (invited)

"Characterization of Degradation of Composites", Workshop on Composites, UCLA, Sept. 12, 1996.

"Lamb Waves from Microfracture Events in Composites Plates", International Workshop on Materials Research With Advanced Acoustic Monitoring Techniques", Max-Planck-Institut für Metallforschung, Tegerness, Germany, Oct. 6-9, 1996 (invited).

"Wave Propagation and Acoustic Emission in Anisotropic Plates", International Acoustic Emission Symposium, Nara City, Japan, Nov. 27-30, 1996 (invited).

"Crack Initiation in Aluminum Plates with Multiple Defects", in International Mechanical Engineering Congress & Exposition, ASME, San Francisco, Nov. 12-17, 1995 (invited).

"Lamb Waves from Microfracture Events in Composite Plates", International Workshop on Materials Research with Advanced Acoustic Monitoring Techniques", Max-Planck-Institut für Metallforschung, Tegerness, Germany, Oct. 6-9, 1996 (invited).

"The Fracture Dynamics in a Dissipative Glass-Fiber/Epoxy Model Composite with AE Source Wave Analysis," International Workshop on Materials Research with Advanced Acoustic Emission Techniques, Max-Planck-Institut für Metallforschung, Tegerness, Germany, Oct. 6-9, 1996 (invited).

"Studying Fracture of Composites with AE Source Wave and Pattern Recognition Analysis," International Seminar on Advanced Acoustic Emission Techniques Applied to Composites, Japan Soc. Materials Science, Doshisha University, Kyoto, Japan, Nov. 26, 1996 (invited).

"Fracture-Mode Determination of Glass-Fiber Composites by Various AE Processing," 13th International Acoustic Emission Symposium, Nara, Japan, Nov. 27-30, 1996.

"Pattern Recognition Analysis of Acoustic Emission from Fatigue of 2024-T4 Aluminum," 13th International Acoustic Emission Symposium, Nara, Japan, Nov. 27-30, 1996.

"Fatigue Damage Modeling and Life Prediction of Titanium Matrix Composites," ASME International Mechanical Engineering Congress and Exposition, Atlanta, Nov. 17-22, 1996.

"An Evaluation of the Performance of Acoustic Emission Systems," 14th World Conf. on NDT, New Delhi, India, Dec. 1996, also at the 40th Meeting, Acoustic Emission Working Group, Evanston, IL, June 1997.

"Wavelet Transform of Acoustic Emission Signals," 40th Meeting, Acoustic Emission Working Group, Evanston, IL, June 1997.

"New Signal Processing Applied to the Analysis of Composite Acoustic Emission," Max Planck Institute, Stuttgart, Germany, June 26, 1997 (invited).

"Multiple Corrosion Defect Considerations in the Life Prediction of Aging Aircraft structures," First Joint DoD/FAA/NASA Conference on Aging Aircraft, Ogden, Utah, July 8-10, 1997.

"Lamb Waves from Microfractures in Composites," Rev. Progr. in QNDE, University of San Diego, July 27 - Aug. 1, 1997 (invited).

"Improved Materials Characterization of Composites Using Plate wave Dispersion Data," Rev. Progr. in QNDE, University of San Diego, July 27 - Aug. 1, 1997.

"Rapid Calculation of the Far Field Response of Isotropic and Anisotropic Plates to a Surface Source," Rev. Progr. in QNDE, University of San Diego, July 27 - Aug. 1, 1997.

"Intelligent Ultrasonic NDE of Materials Degradation," Workshop on Intelligent NDE of Aging and Futuristic Aircraft, University of Texas at El Paso, October 1-2, 1997 (invited).

"Recent Development in Acoustic Emission," Congress on NDE, CORENDE, Mendoza, Argentina, Oct. 1997 (plenary presentation).

"NDT of Aging Aircraft," First Conf. on Aging Infrastructures, National Inst. Safety, Seoul, Korea, Oct. 1997 (invited); 4th Far East NDT Conf., Cheju, Korea, Oct. 1997 (plenary presentation); Kyushu University, Fukuoka, Japan, Oct. 1997 (invited); Tokyo Inst. Technology, Yokohama, Japan, Oct. 1997 (invited); Doshisha University, Kyoto, Japan, Nov. 1997; Aoyama Gakuin University, Tokyo, Japan, Nov. 1997 (invited).

"Elastodynamics of Strongly Heterogeneous Media," ASME International Mechanical Engineering Congress and Exposition, Dallas, Nov. 16-21, 1997 (invited).

"Materials Research and Acoustic Emission," Nagoya Inst. Tech., Nagoya, Japan, Nov. 1997 (invited).

"Recent Developments in Acoustic Emission," Aoyama Gakuin University, Tokyo, Japan, Nov. 1997 (invited).

"Characterization of Materials Degradation due to Corrosion and Fatigue in Aerospace

Structures", AFOSR NDE Program Review, Warner Robins Air Force Base, GA, April 2, 1996 (invited)

"Multiple Corrosion Defect Considerations in the Life Prediction of Aging Aircraft Structures", *Proceedings of the First DoD/FAA/NASA Conference on Aging Aircraft*, July 8-10, 1997, Ogden, Utah .

"Intelligent Ultrasonic NDE of Materials Degradation", Workshop on Intelligent NDE Sciences for Aging and Futuristic Aircraft, UTEP, September 30 - October 2, 1997 (invited).

"Real time Characterization of Materials Degradation Using Leaky Lamb Wave Data", Symposium on Quantitative Non Destructive Evaluation in Integrated Diagnostics ME'97, Dallas, Texas, 16-21 November 1997.(invited talk).

"Elastodynamics of Layered Media", State of the Art Lectures in Deformation and Characterization of Engineering Solids, ME'97, Dallas, Texas, 16-21 November, 1997. (invited)

"Analysis of Acoustic Emission from Corrosion Pits," NDE of Aging Aircraft Track, ASNT Spring Conference, Anaheim, CA, 23-27 March, 1998. (invited).

"Defects Detection and Characterization Using Leaky Lamb Wave (LLW) Dispersion Data", NDE of Aging Aircraft, ASNT Spring Conference, Anaheim, CA, 23-27 March, 1998. (invited).

"A Perturbation Solution for the Interaction of Lamb Waves with Localized Surface Defects", Non-Destructive Evaluation of Aging Aircraft, Airports and Aerospace Hardware, SPIE Conference, 31 March - 2 April 1998, San Antonio, Texas. (invited).

"Composite Material Defects Charaterization Using Leaky Lamb Wave Dispersion Data", Non-Destructive Evaluation of Aging Aircraft, Airports and Aerospace Hardware, SPIE Conference, 31 March - 2 April 1998, San Antonio, Texas. (invited).

"NDE of Rivet Holes in Aging Aircraft Components Using Leaky Lamb Waves", Non-Destructive Evaluation of Aging Aircraft, Airports and Aerospace Hardware, SPIE Conference, 31 March - 2 April 1998, San Antonio, Texas. (invited).

"Wave Propagation in a Plate with Defects", Review of Progress in QNDE, 1998 (invited).

"Rapid Calculation of Lamb Waves in Plates due to Localized Sources", Review of Progress in QNDE, 1998. (invited).

"Probabilistic Issues in the Prediction of the Survivability of Aging Aircraft Structures", International Conference on Mechanics in Design, Nottingham, UK, 6-9 July, 1998. (invited).

"AE Wavefield Calculations in a Plate", Progress in Acoustic Emission, Proceedings of International AE Conference, Big Island, Hawaii, 9-14 August, 1998. (invited).



## Interactions

The research team collaborated with the AF Materials Laboratory in our research on fatigue behavior and damage evolution in Titanium Matrix Composites, with the Jet Propulsion Laboratory in Pasadena and Boeing's McDonnell Douglas Division at Long Beach to develop the leaky Lamb wave technique for the detection and characterization of materials degradation in structural composites in field environments.

A regularly scheduled seminar program was established in which individuals from local industry and government laboratories were invited to give informal talks to our group. A list of recent speakers is provided below:

8/15/97	Dr. M. Nejhad, Boeing/Douglas, "Ceramic Matrix Composites."
8/22/97	Dr. A. Bronowicki, TRW, "Dynamics of Adaptive Structures and Future Trends for Space Applications."
9/26/97	Dr. B. Farahmand, Boeing Aerospace, "Fracture Mechanics of High Risk Parts."
10/24/97	Dr. S. Ghosh, Micropolis, Inc., "Surviving in a High-Tech World."
11/7/97	Dr. J. Goodman, TRW, "Some Mechanics Problems with Spacecraft Materials."
11/14/97	Dr. M. Zaidi, Boeing Products, "NDE in the Aerospace Industry."